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HARD X-RAY AND WIDE FOCUSING TELESCOPES

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Final Report

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Paul Gorenstein

1 Accomplishments of the Program

Introduction The development of a hard X-ray telescope requires new technology for both substrates and coatings. Our activities in these two areas were carried out virtually in parallel during most of the past few years. They are converging on the production of our first integral conical, substrate electroformed mirror that will be coated with a graded d-spacing multilayer. Its imaging properties and effective area will be measured in hard X-ray beams. We discuss each of these activities separately in the following two sections.

2 Substrates

2.1 Electroformed Substrates

Starting with the current state of electroformed Wolter 1 substrates of XMM-Newton, we encountered the following problems in adapting them to the Con-X HXT.

- The gold coating on the interior walls of an XMM replica was deposited without any special effort. Gold is the separation agent which allows the nickel replica to slip off the mostly aluminum mandrel when the assembly is cooled. However, we require that the coating be not gold but rather a depth graded d-spacing multilayer. Consequently, another deposition process is needed.
- We found from the work accomplished so far that the interior surface of a replica made by the same process as an XMM-Newton replica is not as smooth as we desire. After some improvement we achieved the present roughness of about 6 Å rms. While this is fine for XMM-Newton's soft X-ray requirements, we desire as the foundation for a multilayer coating reflecting hard X-rays that the rms roughness of the substrate be 4 Å or smoother.
- With the current mass allowance for the Con-X HXT, electroformed substrates would be too massive with the walls as thick as prescribed by the XMM ratio of shell thickness to diameter. The thickness needs to be reduced by

about 60% without diminishing the stiffness of the replica.

- The cost of producing mandrels for XMM-Newton was rather high. As an ESA "Cornerstone Mission" XMM-Newton was funded more freely than Con-X is likely to be. Furthermore, the HXT is regarded as the junior partner of the Spectroscopy X-ray Telescope (SXT) on the Constellation X-ray Mission. Less expensive procedures for constructing mandrels are required.

The essence of this program is devoted to the multilayer coating effort mentioned in the first bullet above and will be discussed in section 3 We describe below how we are addressing the remaining three problems.

2.2 Replica Smoothness

The reflectivity of a rough boundary in a multilayer is a fraction of the ideal reflectivity of a perfectly smooth boundary. The ratio between the reflectivities of the rough and perfect boundary is called the Debye-Waller factor and is exponentially dependent on the interface microroughness and it also depends on the multilayer d-spacing. Since multilayers for hard X-rays are designed with minimum d-spacings of ≤ 30 Å, their interface roughness must be under 4 Å r.m.s. such that the Debye-Waller factor is no less than 40% (Spiller, 1994). In all the deposition processes in which a substrate is coated with ultrathin layers, the surface roughness of the coating is not better than the substrate roughness, so it is essential to start with substrate surfaces smoother than 4 Å r.m.s. when depositing multilayers for hard x-rays reflection.

The first electroformed substrates that Media Lario produced for us were made with bath temperatures and currents similar to those of the XMM-Newton mirrors. They were smooth on a larger scale appropriate for soft X-rays, however, they did not meet our requirements for smoothness on the smaller scale required for high energy X-rays. The reason is, we think, that the first layers of nickel to settle on the mandrel are not distributed evenly, but formed clusters. The material which is deposited subsequently does not completely fill the gaps between clusters. We are working with Media Lario to reduce the roughness in two ways. One method consists of our evaluating the effect of varying the deposition parameters such as current, temperature, and alloy composition which we observe to have an effect. The second method is

to deposit a buffer layer of tungsten on the mandrel to act as a barrier between the first atomic layers of electroformed nickel and the mandrel. We have sent several flats coated with gold and tungsten to Media Lario where they will make replicas from them to be sent back to us for evaluation.

2.3 Substrate Mass

To meet the stringent mass allowance of the Con-X HXT, the replicas should be 60% thinner than the prescription of XMM-Newton for the ratio of wall thickness to diameter. However, the replicas should remain sufficiently stiff to satisfy our resolution goal of 15 arc seconds. We believe this is possible by finding new nickel alloys that form a stiffer product. Media Lario is indeed offering to make replicas from nickel alloys that are expected to be stiffer. Part of our research plan will be to evaluate them.

We are also beginning an informal collaboration with the Marshall Space Flight Center X-ray optics group who have access to an electroforming facility that is operated by the University of Alabama at Huntsville. They are also proponents of electroformed telescopes for HXT but with an approach that does not (at least according to their previous statements) utilize multilayer coatings. The MSFC/UAH group also claim to have developed stiffer alloys plus a bonus of 10% lower density. We will have the opportunity to evaluate that material. Currently Media Lario and the U. of Alabama regard their work as proprietary. However, as an independent research group, we have our own separate objectives. We will be in a unique position to compare the materials while still respecting the propriety of both companies. We are encouraged that the mass reduction goal appears to be attainable.

2.4 Production of Mandrels

Mandrels are an essential relatively expensive component in the fabrication of integral shell substrates. Each of the 80 Wolter 1 substrates of our Con-X HXT design requires a separate mandrel. The cost estimates for a complete single conical mandrel we received from potential vendors exceeded our budget. We found that the materials and services required could be purchased individually for far less than the cost of a complete mandrel. Consequently we decided to manage the production ourselves. We purchased a hard forged hollow aluminum cylinder (30 cm OD, 15 cm ID) plus four 10 cm diameter 1 cm thick coupons for testing from a local metal vendor. Machining ser-

vices were purchased from OFC Diamond Turning, of Keene, NH. Tech Metals of Dayton OH applied a polishable coating of electroless nickel to the aluminum. The Brera Observatory optics shop agreed to do the final polishing of the mandrel. Our experience was rather good in that the final cost to us of the mandrel was considerably less than the estimates for a complete product. The mandrel we constructed is shown in Fig. 3 before it was sent to Italy Brera for final polishing and then to Media Lario for replicating a mirror substrate. A replica from an incompletely polished mandrel which we will soon coat is shown in Fig. 4.

The most expensive part of the process by far was the diamond turning machining (especially with the added cost of correcting a failed attempt at a short-cut). It amounted to about 2/3 of the total plus the correction cost. In retrospect we believe the number of pieces comprising the mandrel can be reduced either by elimination or integrating into the main section two removable extension pieces whose function was solely to assure that the mandrel would be polished smoothly along its entire length. The HXT mandrels would be 70 cm long so a small loss at each end is tolerable. In addition, the MSFC group has suggested that diamond turning could be replaced by a much less costly precision grinding process from a vendor they have found that would leave the surface of the mandrel almost as smooth as diamond turning for the final polishing. If both measures prove to be effective the cost of a mandrel would be reduced to below \$10K.

3 Coatings

3.1 Introduction

Over the past few years we have constructed and brought into operation a facility for coating hard X-ray optics. The principal motivation for constructing our multilayer chambers was to build a facility with the high capacity needed to coat our prototype substrates quickly and responsively. In the design and operation of these chambers we have applied knowledge about materials, deposition techniques, and diagnostics that have been previously reported by many others. Our success is measured by the degree to which we have been able to match the high quality of their multilayer coatings in a chamber that operates completely until the control of software and has the capacity to coat about 3000 cm² of area per day with hundreds of layers of the heavy and light materials

with excellent uniformity and adherence to the specifications on thicknesses. It is unique in having the ability to coat the interior walls of integral cylinders with a diameter down to 15cm to accommodate the geometry of our prototype for the Con-X HXT.

In particular, we have concentrated on multilayer coatings which will increase the energy range of a 10 meter (focal length) class telescope from the present day limit of ≈ 10 keV to ≈ 100 keV and higher. The use of these coatings to extend the energy band of X-ray telescopes was first proposed by Christensen et al. (1991) and the first reported measurements of such coatings on test substrates were presented by Joensen et al. (1994). Over the past several years since this initial work, several groups, including ours, have been involved in developing these coatings (Craig et al., 2000; Tawara et al., 1996). The coating facility was designed and constructed based upon two precepts. The first was that the method of deposition had to be capable of uniformly coating large areas. This is required to assure that the method is indeed applicable to large area telescope systems like the Con-X HXT and HSI. For this reason we selected DC magnetron sputtering and not, for example, ion beam sputtering. The latter can actually produce somewhat higher quality coatings but only on small areas at a time, and therefore is not applicable for the large area optics needed for Con-X type missions. The second precept was that the system had to be capable of coating the interior surface of integral conical shells (Wolter 1 optics in this case) as well as flat or curved open substrates. Our facility includes two high vacuum chambers for DC magnetron sputter deposition of multilayer films and an X-ray reflectometer with a 2 circle goniometer for characterization studies. This facility has been described in detail (Romaine, 1997,1998) and we refer the reader to the fac phs of our setup. The R&D chamber (figure 1 on the facility page) was designed to coat flat substrates up to 3 inch diameter with a quick turn around time. This allows us to fabricate several test depositions a day for evaluating various multilayer material combinations and coating parameters. Several different materials have been used to fabricate test multilayer coatings on flat substrates in this chamber. Reviews of results for W/Si, W/C, Pt/C, Mo/Si, Ni/C and WSi₂/Si have been presented earlier (Ivan et al., 1998a; Ivan et al., 1999). The R&D chamber continues to play an important role in testing new materials or material combinations.

The larger MLPC chamber was designed specif-

ically to deposit onto the inside surface of integral cylindrical optics up to 24 inches long. As described previously, to date, telescopes with integral optics are the only ones which have achieved an angular resolution of 15 arcsec or better. Although we have concentrated on creating a facility that would coat the inside surface of an integral optic, this same facility can be used to coat flats, and curved surfaces of various shapes made of various materials for segmented substrates. It has in fact been used to coat prototype segmented telescope substrates in connection with other collaborators (see Romaine et al. 2000).

The cathodes are positioned inside the optic during deposition. The smallest diameter integral optic which our system can accommodate in its current configuration is approximately 6 inches. There is no minimum size for flats or for open curved substrates. This system has the capacity to coat several thousand square centimeters of area per day.

We are also evaluating the process of transferring an entire multilayer coating from mandrel to substrate in connection with our collaboration with Brera and more recently on an informal basis with MSFC. We apply the multilayer coating to a mandrel. They (i.e. Media Lario and MSFC) perform the electroforming and separation. We evaluate the replica. So far, our work has involved only flats and this process is still in progress. It will be applied to cylindrical mandrels later. However, good results were obtained by Brera (Citterio et al, 1999) using epoxy replication, which for small flats is a much more convenient process than electroforming. This bodes well for the process succeeding with electroforming.

The third major piece of equipment is an X-ray reflectometer. This is equipped with a $Cu - K_{\alpha}$ tube, a monochromator, a 2-circle goniometer, a scintillator detector and several slits to align and define the beam. The 8 keV reflectivity as a function of angle provides a quick and convenient measurement of the roughness of a bare substrate and also of the multilayer coatings. It is especially sensitive in testing constant period multilayers because there are characteristic Bragg peaks through several orders whose amplitude, position and shape reveal the multilayer's quality. An example of such Bragg peaks can be seen in figure 8 which displays 1st and 2nd order Bragg peaks. The position of the peak is defined by θ in the Bragg equation, $n\lambda = 2d\sin(\theta)$, where θ is very sensitive to small changes in d . A variation in d spacing will be seen in a broadening of the peak and the microroughness of the interface will effect the amplitude

of the peaks (i.e. the maximum reflectivity).

We have recently purchased a 1-dimensional detector which will give us the capability to do non-specular scans; something that is too time consuming to be practical with our current detector. These scans are necessary to decouple the effect of surface roughness from that of interface mixing. We use the term microroughness to include both the physical surface microroughness and intermixing of materials at the interface.

To date we have been successful in fabricating both constant-d and depth graded-d multilayer coatings on several different types of substrates. The majority of reflectivity measurements have been taken at CuK energy, but we have progressed to measuring the reflectivity at higher energy at the National Synchrotron Light Source at Brookhaven National Laboratory.

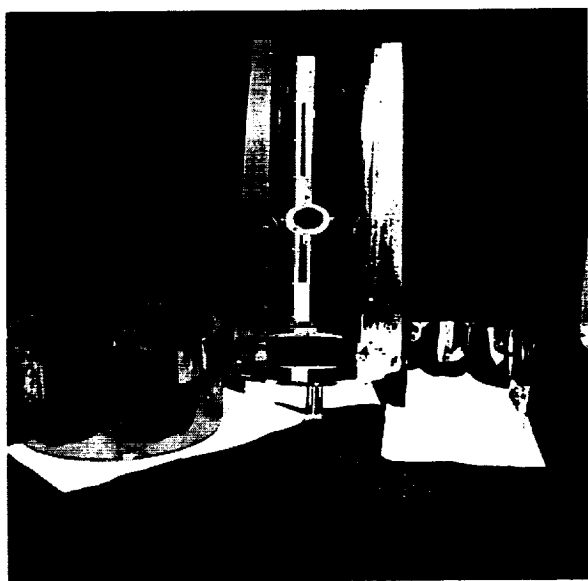


Figure 1: Examples of substrates coated in the MLPC chamber; on the left is an integral glass optic, in the lower right corner is a piece of coated slumped glass, in the center is the substrate holder that interfaces to the rotation stage in the coating chamber; it is shown loaded with three 120 deg sections of segmented glass and three silicon wafers.

3.2 Depositing Multilayers Upon Integral Substrates

As discussed earlier, SAO is collaborating with the Brera Observatory to produce integral electroformed

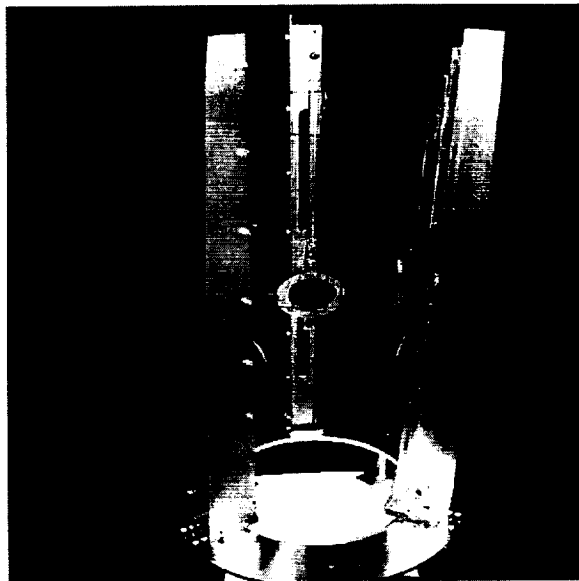


Figure 2: Close up of sample holder with three 120 degree segments of slumped glass mounted along with a silicon wafer below each piece of glass. The silicon wafer acts as a coating witness sample. The slumped glass is 20 cm in height.



Figure 3: Mandrel produced by SAO - after diamond turning but prior to superpolishing.

shells for prototypes for the Constellation-X HXT. The first mandrel has now been fabricated (see fig. 3) and polishing of the surface is almost complete. We have received a prototype replica (see figure 4) which was electroformed before the polishing of the

mandrel was completed. We expect future replicas to be smoother as a result of finer polishing. We are still refining the parameters of the electroforming process and studying the effect of using buffer layers of W, if necessary, to moderate the residual roughness of the top surface of the electroformed material. Figure 5 shows the prototype in the XRR setup where we used a pencil beam to measure the specular reflectivity at 4 azimuthal locations (0, 90, 180 and 270 degrees). The data shown in the right of figure 5 is typical of all four data sets taken and fits a microroughness of 6 Å. In the next phase we will deposit a depth graded multilayer on this prototype and measure the reflectivity as a function of angle at high energy (using BNL). We also plan to measure the angular resolution, directly in a broad parallel hard X-ray beam at MSFC or other possible locales. This will be the first direct measurement in hard X-rays of the angular resolution of a multilayer coated electroformed shell. Although we expect future replicas to be better we still expect that testing this one will provide a useful indication of our progress and of our test procedures.

We are investigating two complementary methods to deposit multilayers on the interior surface of integral shells. A nominal Con-X HXT design contains substrates from 12 to 30 cm diameter. For diameters 15 cm or larger, our prime approach is depositing the multilayer directly upon the inside surface of the shell with our own facility which is unique in having that capability (as mentioned above). For this work the two linear cathodes with the heavy and light materials would be repositioned when required to maintain the distance between target and substrate within the desired range of 6 to 9 cm.

Adding substrates with diameters between 12 and 15 cm would increase the total number of substrates by 29%, the mass by only 19% and the effective area at 60 keV by 40%. Therefore it is worthwhile including them. For those substrates we would employ the other coating procedure mentioned above. The mandrel is coated with the multilayer and electroforming occurs over it. The entire multilayer is transferred from mandrel to substrate during separation. A complete Con-X HXT with 12 mirrors has about 1000 Wolter 1 substrates.

The facts that the deposition process is completely controlled by software and that the cost of duplicating the chamber is rather modest suggest that it would be cost effective for multiple chambers to operate simultaneously. Multiple chambers would also eliminate the necessity for repositioning cathodes and

facilitate the use of different material combinations (e.g. W/Si, Pt/C, or Mo/Si) with each combination optimized for a particular range of graze angles for maximum effective area and bandwidth.

Our experience with our computer controlled deposition process indicates that to coat that many substrates it is cost effective for three chambers to operate simultaneously. Three chambers would also facilitate the use of three different material combinations (e.g. W/Si, Pt/C, or Mo/Si) according to which is best for the range of graze angles.

Due to the magnets, cooling water, etc. which make up dc magnetron cathodes, there is a lower limit to the size of dc magnetron cathodes that can be fabricated. This implies a minimum diameter integral optic that can be coated in the manner we describe. Therefore, for substrates with diameter smaller than 15cm, we would employ another procedure, transferring the entire multilayer from mandrel to substrate. The graded-d spacing multilayer coating is deposited upon the mandrel (over a separation agent) with the layers in reverse order, gold preceded by a thin chromium binder layer is evaporated over the reverse multilayer, and the nickel substrate is electroformed over that. Following separation the multilayer is on the substrate in the correct order. We have shown that transferring an entire multilayer is effective with epoxy replication on polished flats (Citterio et al, 1999). We are now applying it to electroformed flats and will progress to small diameter cylindrical mandrels. Our multilayer deposition facility is capable of coating the exterior of cylinders as well as the interior surface. The process of reverse coating the exterior of the mandrel would be more complicated than direct coating of the interior of the replica substrate. Therefore, we will reverse coat mandrels only for substrate diameters that are too small to coat directly. For the Con-X HXT we expect that this will be no more than 30% of the total number of shells.

3.3 MLPC Chamber: Uniformity Studies

The coating requirements for X-ray optics are stringent - a different coating thickness will reflect a different wavelength. Mao et al. (1997) have addressed this issue of uniformity and find, for example, that a drop in d-spacing of 15% across the optic would result in a reduction of the collecting area by approximately 15%. In addition, they demonstrated for HEFT (Harrison et al., 2000) that one "can tolerate a 5% change in the bilayer thicknesses across the mirror surfaces without having a significant influence on the through-

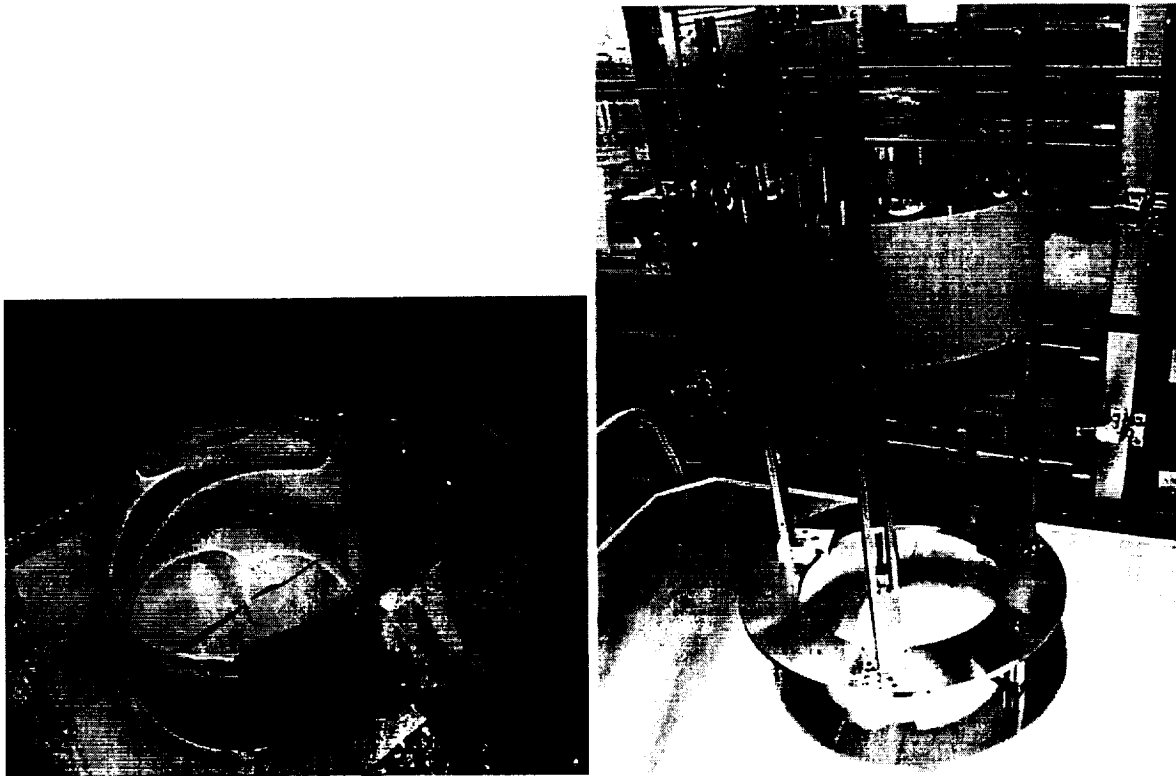


Figure 4: Left: Electroformed single conical replica; diameter 28 cm, shell height 14 cm. fabricated by Media Lario (Italy). right: shell on mounting platform used in coating chamber.

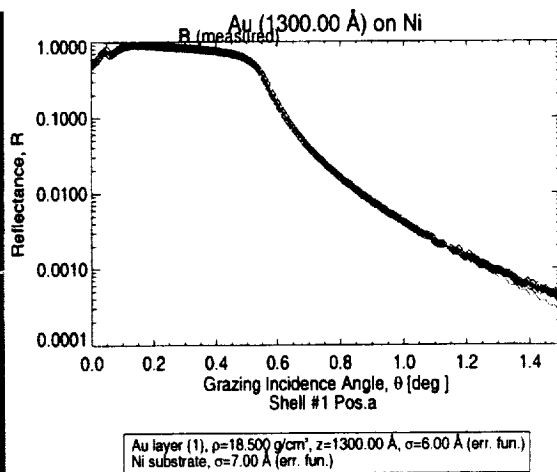
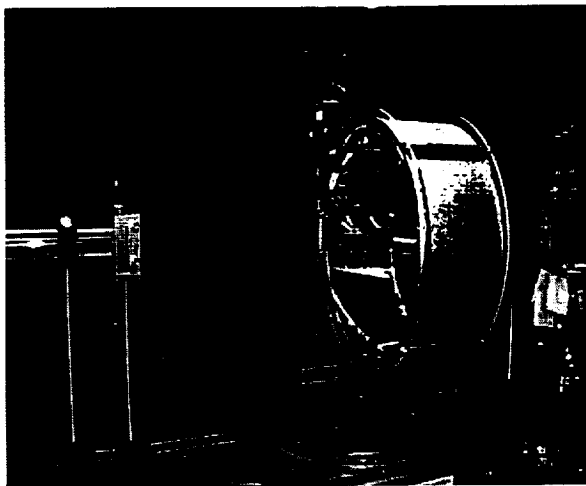


Figure 5: Left: shell mounted in XRR setup; right: 8 keV XRR data (open diamonds) and model (solid line) for gold coated replica surface - 6 Å microroughness.

put and/or field of view of the telescope" (Mao et al., 1997). Therefore, to maximize the collecting area, we place stringent requirements on the uniformity of the coatings.

Most sputter coating facilities use a pass-by type system where the substrate to be coated passes by the sputtering target which is parallel to it. Coating flat substrates uniformly in this manner is straightforward. Since the coating thickness deposited is proportional to the source-substrate distance, coating a curved optic in this way will put a thicker coating on the part of the optic that passes closer to the target. This can be overcome by designing baffles to decrease the coating in one section in an attempt to put down a more uniform layer. Due to the design of our system, and the symmetry of the substrate-source distances, we expect to achieve excellent uniformity on curved optics (with no need to add baffles to adjust the coating). Over the past year we have carried out some extensive work to look at both the linear and azimuthal uniformity of our coatings on several different substrates (Bruni et al., 1998; Romaine et al., 1998b, 2000). We have concentrated our work on W/Si multilayers which is one of the materials of interest for Constellation-X (Pt/C is also a material of interest for Constellation-X, but due to the expense of obtaining a Pt target we have concentrated our efforts in the MLPC chamber on W/Si. Several studies of Pt/C have been carried out in the R&D chamber.)

The initial uniformity studies were carried out on silicon wafers and to do this a mounting surrogate was used to fixture several silicon wafers azimuthally and vertically on a 'cylindrical surface of revolution' in the chamber to test the uniformity of the coating over an area sufficiently large to encompass an HXT optic (at least 40 cm in height).

To test the coating uniformity, we chose to use constant d-spaced multilayer coatings rather than the graded d coatings that will be used on the flight optics. Constant d coatings are much less 'forgiving' of changes in d-spacing; a small change in layer thickness produces a clearly recognizable change in the Bragg peaks of the specular reflectivity.

We have presented earlier (Ivan et al., 1998; Romaine et al., 1998) initial results from the MLPC chamber of specular reflectivity data on samples with both constant and graded d-multilayer coatings. Over the past year we have both automated and optimized our depositions and have reached our goal of 3.5 Å microroughness and here we report we have achieved

better than our goal of $\pm 5\%$ thickness variation.

The MLPC chamber was designed to be flexible and so has the capability of coating many substrates in addition to flat wafers and to date many different substrate types and geometries have been coated in this chamber. These include: integral glass 'optics', slumped glass segments (supplied by the HEFT team, see Craig et al., 2000), plastic foils, silicon wafers, float glass and super polished fused silica. Some of these optics are shown in figure 1. As can be seen from the substrate holder shown in figure 1, we have the capability to load 'a full set' of segmented optics into the chamber for coating at the same time; in addition we can load witness samples such as the 2 inch silicon wafers shown here which can be used to characterize the coating run - thereby avoiding unnecessary exposure of the flight optics. Coating a full set of segmented optics in the same run saves time and also exposes all the segments to the same coating conditions.

In addition to our tests on silicon wafers, we received several slumped glass substrates from the HEFT team members (Craig et al., 1998) to use for uniformity tests while we awaited the completion of our mandrel. Each slumped segment was 20 cm in length and slumped to span 120 deg with a mean radius of approximately 11 cm. The segments were mounted for coating as shown in figure 2, three segments were mounted to form a cylindrical optic and silicon wafers were mounted above and below the optic to act as witness samples. These were coated with a W/Si constant d multilayer coating of $N=60$, $d=29.0$ Å and $\gamma=0.40$. Specular reflectivity measurements were taken (at Cu K_α) of all the samples to compare the coating uniformity.

In addition, two pieces of the segmented glass (samples S1 and S3) were mapped extensively to look at uniformity within a single segment. Figure 6 shows the mapping of S1: 5 different angles were used (0, ± 30 , ± 45 degrees) and 5 different linear positions (0, ± 3 cm, ± 6 cm). Figure 6a shows the mapping for the X-ray reflectivity (XRR) scans of S3: 5 different angles were measured (0, ± 10 , ± 20 degrees) and 3 linear positions (0, ± 6 cm) were measured at each angle. In all of these figures 0 degrees, 0 cm is at the center of the segment.

All XRR scans were taken with the slit set such that the beam impinging on the sample covers 5 cm in length when the angle of incidence is 0.2 degrees. This is set such that the beam does not fall off the

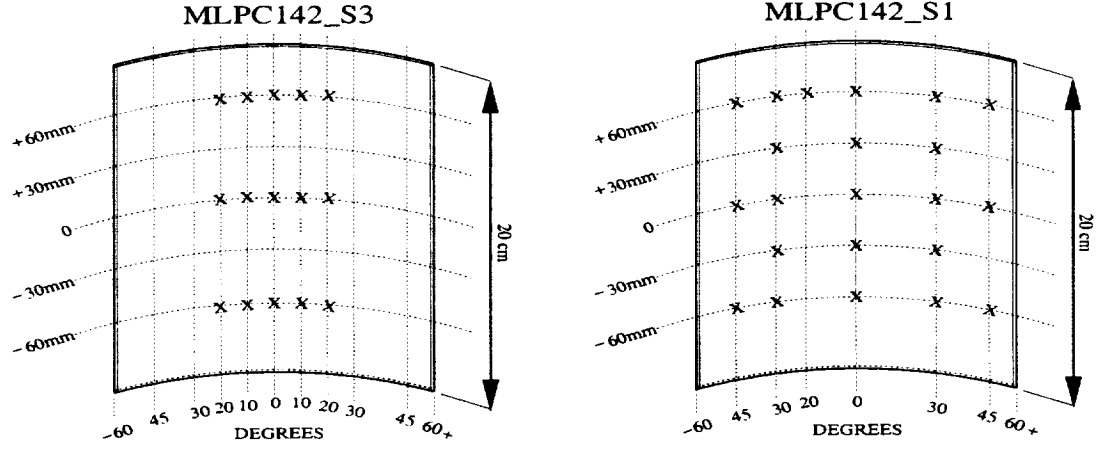


Figure 6: Sketch showing the spatial distribution of the XRR data scans for sample S3 (figure on left) and S1 (figure on right) of run 142; W/Si, N=60.

sample when scanning at the outermost point (6 cm from the center). Each data set was fit using IMD software of David Windt (1998). The fits are very sensitive to d-spacing (sum of W and Si thickness for each layer) and this parameter is known to $\pm 0.1 \text{ \AA}$. In figure 7a we show a plot of reflectivity vs. grazing angle for the central point of both S1 and S3 samples (which were located at 120 deg from each other in the chamber) which show a d-spacing variation of 3% between the 2 samples; and in figure 7b we show similar data for 3 scans along the center of sample S1 - where the fits indicate a variation of approximately 1.4% among these scans.

A summary of the results of all the measurements for the 2 coated segments was presented in Romaine et al.(2000). The results for S1 yield a mean value for $d=29.7 \text{ \AA}$ with $\text{std}=0.53 \text{ \AA}$; for sample S3 we find a mean value for $d=28.74 \text{ \AA}$ with standard deviation $=0.82 \text{ \AA}$. This data suggest a thickness spread across S1 of $\pm 1.8\%$ and across S3 of $\pm 2.8\%$, well within the limits suggested by Mao et al (1997) for a Con-X type optic. In addition, taking the data for S1 and S3 collectively to sample now a 240deg section of an optic, we find a mean value for $d=29.3 \text{ \AA}$ with $\sigma=0.81 \text{ \AA}$, a variation of less than 3%. We note that these are test slumped glass segments whose figure is not perfect, therefore part of the thickness variation is due to the imperfection of the figure of the substrate itself.

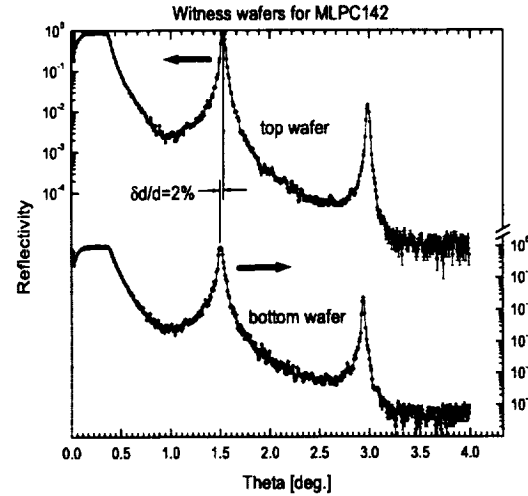


Figure 8: Reflectivity vs. grazing angle (8 keV) scans taken of the silicon wafer witness samples coated in run 142. These were mounted above and below the slumped glass with a vertical spacing of 12 inches between them. The surface of the silicon wafers is smoother than the slumped glass and the modelled microroughness is 3.0 \AA for both wafers. These 2 wafers show a 2% variation in modelled d-spacing.

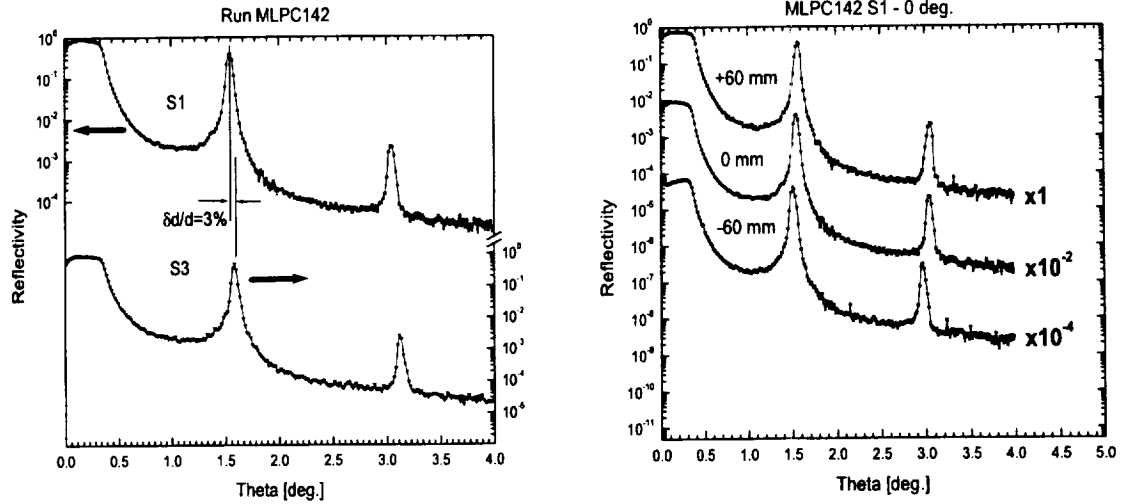


Figure 7: Reflectivity vs. grazing angle (8 keV) for constant d-spaced multilayer: W/Si, $N=60$, $d=29.5$ Å, $\gamma=0.40$. Left figure: these 2 data sets were taken from scans of the center of 2 pieces of slumped glass mounted 120 degrees apart in the chamber. The d spacing from the model fits is 28.45 Å and 29.4 Å. Right figure: three scans of reflectivity vs. grazing angle (8 keV) for sample S1; scans were taken along the centerline of the sample and cover 18 of the 20 cm. substrate length. The variation in period is $\pm 1.4\%$ across the 3 scans.

Figure 8 shows the sample scans for the two silicon witness wafers that were mounted directly above and below the slumped glass segments, with a vertical separation of 30 cm. The model for these two sets of data shows a 2% variation in d-spacing, and falls within the standard deviation of the full set of measurements for this run.

The modelled interface roughness for all the slumped glass data scans was 4.5 - 5.5 Å; this is to be compared with the modelled interface roughness for the silicon wafers which was 3.0 Å. The surface of the Si wafers is much smoother than that of the slumped glass and the difference in microroughness can be attributed to this difference in the substrate surfaces. (We should add that these slumped glass substrates do not represent the best substrates produced by the HEFT project.)

In conclusion, we have analyzed in detail a 240 deg (by 20 cm high) segment of an optic using constant d multilayers and find our coating well within the necessary uniformity for Constellation-X requirements. We expect the coating of the integral shell will yield similar results.

Depth Graded Multilayers Figure 9 shows 8 keV reflectivity vs. grazing angle scans for four different silicon wafers that were coated together in the same run with an $N=200$ graded-d W/Si multilayer using a power law thickness variation (Joensen et al., 1995) with $d_{min}=25$ Å and $d_{max}=220$ Å. The wafers were mounted to span approximately 270 degrees in azimuth and 5 inches in height. The model fits to this data show that all the plots are fit by the same set of parameters; clearly the uniformity achieved here is well within our requirements for a Con-X type mission. As mentioned above, reflectivity measurements of depth graded multilayers are 'more forgiving' than fits of constant d coatings where the sharp Bragg peaks put a tighter constraint on the fit.

4 High Energy Measurements

The majority of our reflectivity measurements to date have been specular reflectivity measurements taken at 8 keV. We have just begun a collaboration at Brookhaven National Laboratories (BNL) which will provide us with beam time for a range of energies from 40 keV to 130 keV, this upper limit being above the cutoff energy currently planned for Constellation X, and consistent with higher energies planned for future mis-

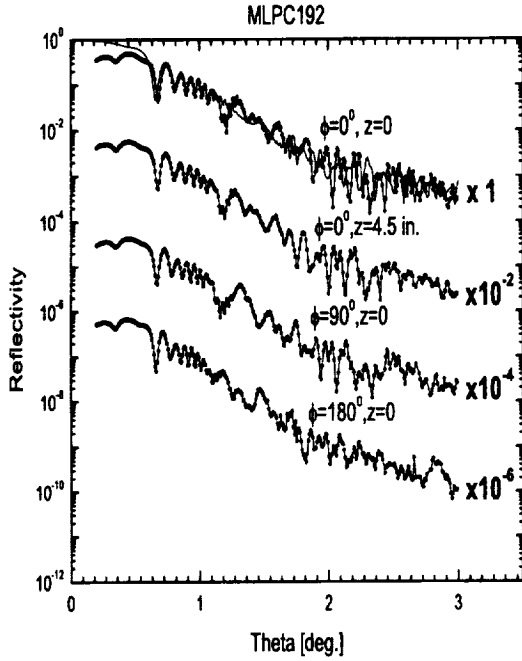


Figure 9: Measured reflectance as a function of graze angle, taken at $\text{Cu-K}\alpha$ for 4 different silicon wafers coated for uniformity tests; the wafers were placed in the coating chamber to cover an area of 270 degrees in azimuth and 5 inches in height. The coating parameters were $N=200$, $d_{\min}=25 \text{ \AA}$ and $d_{\max}=220 \text{ \AA}$. Fit to each data set showed an interface roughness of 3 \AA . Each data set is shifted by 2 orders of magnitude for clarity. See text for more details.

sions. We also have a collaboration to obtain beam time on the European Synchrotron Research Facility which will provide us with more high energy measurements.

We present below our first set of high energy data for depth graded multilayers designed to yield high reflectivity at energies exceeding 20 keV. All data were taken at the National Synchrotron Light Source at Brookhaven National Laboratory on X17B1 beamline. The x-ray beam was tuned to monochromatic energies using a Si(111) double crystal monochromator. Measurements of reflectance as a function of grazing angle were taken for 14 different beam energies ranging from 40 - 130 keV (in addition, 8 keV data was taken for all samples at SAO).

Figure 10 presents data for sample WSi201 which was designed with $N=350$ to provide some reflectivity above the W/K-absorption edge (69.5 keV). Plots 10 (a) and (b) show reflectivity as a function of energy for the graze angles 6 and 9 arcmin, which are reasonable for the inner shells of Constellation-X. The solid line is the model and the data points plotted are those taken from measurements at BNL. The 9 arcmin data shows a reflectivity of $\approx 40\%$ from 40 - 69.5 keV then decreases to $\approx 10\%$ for 70 - 100 keV. As we move to lower grazing angles (see 10 a), the reflectivity increases (as expected) in the band 70 - 100 keV. The plots of figure 10 (c) and (d) show reflectivity as a function of graze angle and scattering vector respectively for a subset of the data taken for WSi201. We point out the drop in reflectivity at the W/K-edge (69.5 keV) which is easily seen in figure 10 b.

As discussed in section ??, we have started to design grazing incidence optics for energies well in excess of the 90 keV upper limit currently discussed for Constellation-X. For higher energy reflecting optics we will move toward smaller d-spacing. For W/Si multilayers using argon sputter gas the smallest layer thickness that is achievable while keeping the interface smooth is approximately 10 \AA of tungsten (Ivan et al., 2000).

Additional Characterization We use a number of different tools to fully characterize the films. Atomic Force Microscopy (AFM), Transmission Electron Microscopy (TEM), Rutherford Backscattering (RBS) and Auger Spectroscopy are tools we use for supplementary analysis. AFM measures only the physical roughness of the uppermost surface or of the underlying substrate prior to deposition. It is most useful for

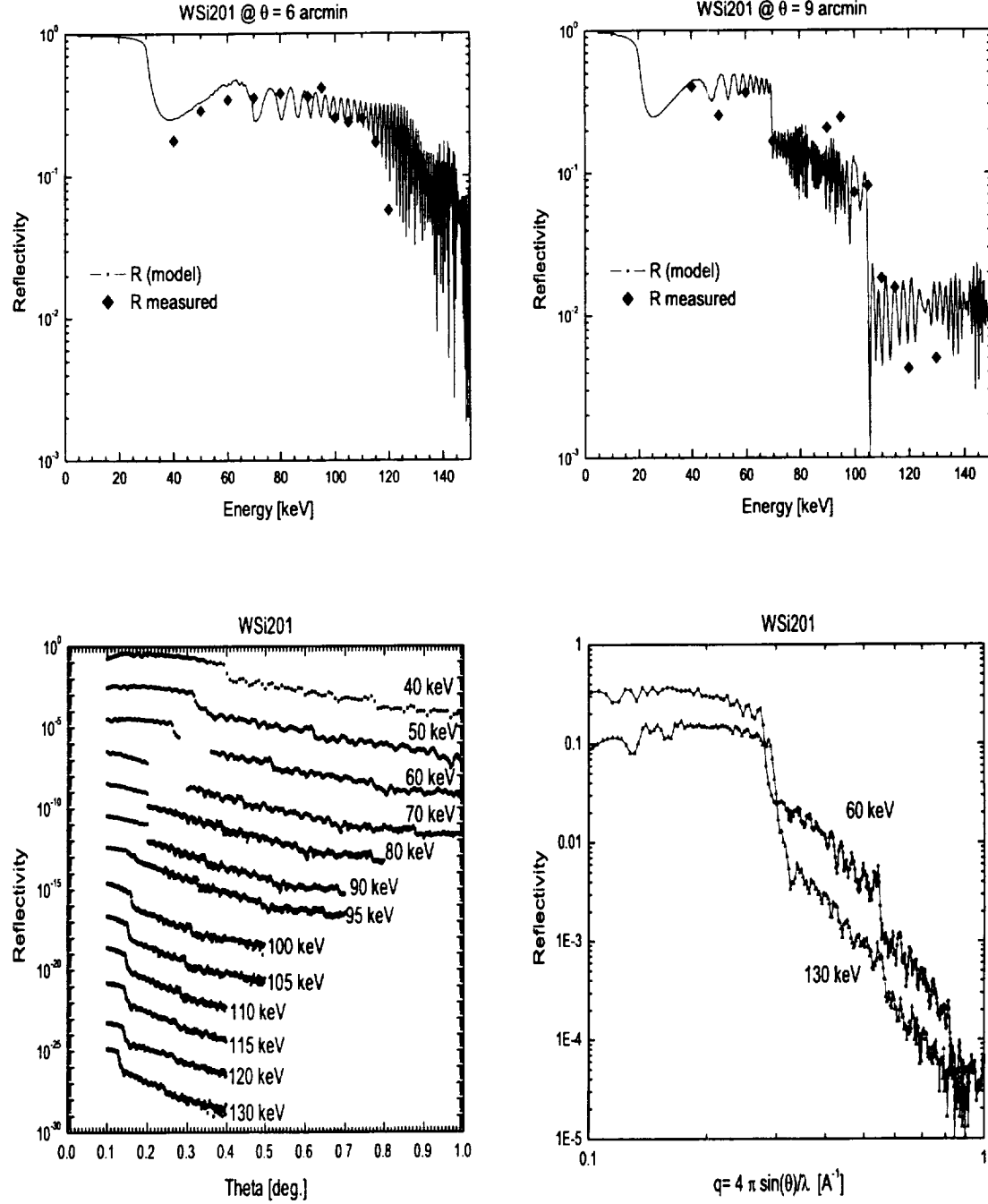


Figure 10: top left/right (10a,b): reflectivity as a function of energy (for 6/9 arcmin), for sample wsi201 ($N=350$, $d_{\min} = 23 \text{ \AA}$, $d_{\max} = 111 \text{ \AA}$). Design is solid line, measured data represented by filled symbols; bottom left(7c): reflectivity as a function of graze angle data taken at BNL for several different energies; bottom right ((10d): the reflectivity vs momentum exchange vector q for sample WSi201 measured at several different energies, 40 keV to 130 keV. The scattering (or momentum exchange) vector q is equal to $4\pi/\lambda * \sin(\theta)$, where λ is the photon wavelength and θ is the grazing incidence angle. (The data sets are shifted a factor of 100 for clarity and the energy for each dat set has been indicated.)

screening substrates and determining the physical roughness of a single layer of deposited material. There is a good correlation between the AFM roughness on its finest scale, 1 micron total scan in 256 steps, and the roughness provided by the X-ray data. TEM is used to provide qualitative information about the interface; RBS can be used to provide density measurements of a film or to look for contamination. These tools provide a more complete picture of the films that are grown. Much of this type of data has been presented in previous meetings (Sokasian et al., 1997; Everett et al., 1998; Hussain et al., 1997a; Hussain et al., 1997b; Schwartz et al., 1999).

5 References

- R.Bruni, K.Byun, A.Ivan, A.Hussain, P.Gorenstein, S.Romaine, "Uniformity of Coatings for Cylindrical Substrates for Hard X-Ray Telescopes", poster presented at MRS Meeting, Boston, 1998.
- W.W.Craig, C.J.Hailey, M.Jimenez-Garate, D.L.Windt, F.A.Harrison, P.E.Christensen, A.M.Hussain, "Development of thermally formed glass optics for astronomical hard x-ray telescopes", *Optics Express*, vol. 7, no.4, 2000.
- F.E.Christensen, A.Hornstrup, N.J.Westergaard, H.W. Schnopper, J. Wood, and K.Parker, *Proc. SPIE*, vol. 1546, 1991, pp160-167.
- F.E.Christensen, W.W.Craig, D.H. Windt, M.A. Jimenez-Garate, C.J.hailey, F.A. Harrison, P.H.Mao, J.M.Chakan, E.Ziegler, V. Honkimaki, "Measured reflectance of graded multilayer mirrors designed for astronomical hard x-ray telescopes", *Nucl.Inst.Meth. A*, vol. 451, no.3, 2000, pp.572-581
- F.E.Christensen, W.W.Craig, C.J.Hailey, M.A.Jimenez-Garate, D.L.Windt, F.A.Harrison, P.H.Mao, E.Ziegler, V.Honkimaki, M.Sanchez del Rio, A.K.Freund, M.Ohler, "Hard X-ray characterization of a HEFT single reflection prototype", *Proc.SPIE*, vol. 4012, 2000, pp.626-638
- W.W.Craig, F.E.Christensen, T.A.Dekker, C.J.Hailey, F.A.Harrison, R.M.Hill, M.A.Jimenez-Garate, P.H.Mao, S.M.Schindler, "Hard X-ray optics for the HEFT balloon borne payload: prototype design and performance", *SPIE Proc.*, Vol. 3445, 1998.
- J.Everett, R.Bruni, A.Hussain, A.Ivan, S.Romaine, K.Byun, P.Gorenstein, 1998, "Characterization of Multilayers for X-Ray Optics", presented at AAS meeting in Washington D.C.
- J.A.Folta, S.Bajt, T.W.Barbee, Jr., F.R. Grabner, P.B. Mirakarimi, T. Nguyen, M.A. Schmidt, E. Spiller, C.C.Walton, C.Montcalm, "Advances in multilayer reflective coatings for extreme ultraviolet lithography", *Proc. SPIE*, vol. 3676, 1999, pp. 702-709
- Hassan, M et.al., 1992, *Vacuum*, Vol. 43. pp.55-59
- Hussain, A., et al. 1997 "Studying Density vs. Ar-pressures for Optimization of DC-magnetron Sputter Deposition of Ni/C Multilayers for Hard X-ray Telescope", *Proc. SPIE*, Vol.3113, p.260
- Workshop on: Nanometer Scale Methods in X-Ray Technology, Portugal
- K.D.Joensen, P. Voutov, A. Szentgyorgy, J.Roll, P.Gorenstein, P.Hoghoj, F.E.Christensen, "Design of grazing-incidence multilayer supermirrors for hard X-ray reflectors", *Applied Optics*, vol.34, no.34, 1995, pp7935-7944.
- Ivan, A et. al., 2000, "Ultrathin Period Multilayers for Hard X-ray Imaging Telescopes", presented at MIT Doctoral Thesis Seminar , 12 April 2000
- A.Ivan, R.Bruni, K.Byun, J.Everett, P.Gorenstein, S.Romaine, "Multilayer coatings for focussing hard X-ray telescopes", *MRS Proc.* Vol. 551, 1999. pp 297-302.
- A. Ivan, S.E.Romaine, R.J.Bruni, J.E.Everett, P.Gorenstein, 1998, "Characterization of graded d-spacing Multilayers for Hard X-ray Telescopes", *Proc. SPIE*, Vol. 3444, p.556-563.
- P.Mao, F.Harrison, Y.Platonov, D.Broadway, B.Degroot, F.E. Christensen, W.W.Craig, C.J. Hailey, "Development of grazing incidence multilayer mirrors for hard X-ray focusing telescopes", *Proc. SPIE* Vol.3114, 1997, pp.526-534.
- G.Pareschi, O.Citterio, M.Ghigo, F.Mazzoleni, A.Mengali, C.Misiano, "Nickel-replicated multilayer optics for soft and hard x-ray telescopes", *Proc. SPIE*, Vol. 4012, 2000, pp.284-293.
- S.E.Romaine, J.E.Everett, R.Bruni, A. Ivan, P. Gorenstein, M.Ghigo, F. Mazzoleni, O.Citterio, J.Pedulla, "Progress in replication of substrates for multilayer coatings", *Proc. SPIE*, vol. 3444, 1998, pp.564-568.
- S.E.Romaine, J.E.Everett, R.Bruni, A. Ivan, P. Gorenstein, "Characterization and Multilayer Coating of Cylindrical X-ray Optics for X-ray Astronomy", *Proc. SPIE*, Vol.3444, 1998, p.552-555.

- Romaine. S., Hussain. A., Everett, J, Clark, A., Bruni, R., Gorenstein, P., Ghigo, M., Mazzoleni, F., Citterio, O., and Pedulla, J., 1997, "Application of Multilayer Coatings to Replicated Substrates", Proc. SPIE Vol.3113, p.253
- S.E.Romaine, 2000 ????
- M.P.Ulmer, R.Altkorn, A.Madan, M.Graham, Y.-W.Chung, A.Krieger, C.Liu, B.Lai, D.C.Mancini, P.Takacs, "The fabrication of Wolter I multilayer coated optics via electroforming: an update", Proc. SPIE, vol. 3773, 1999, pp.113-121.
- C.Schwartz, K.Byun, R.Bruni, A.Ivan, S.Romaine, P.Gorenstein, 1999, "Multilayer Optics for the Next Generation X-ray Telescope: Fabrication, Characterization and Application", presented at AAS meeting in Washington D.C.
- A.Sokasian, R.Bruni, A. Clark, S.E.Romaine, P.Gorenstein, 1997, "Multilayer Characterizations", presented at AAS Meeting.
- Y. Tawara, K. Yamashita, H.Kunieda, K. Haga, K.Akiyama, A.Furuzawa, Y. Terashima, P.J. Serlemitsos, "Multilayer supermirror coating for hard X-ray telescope", SPIE Proc., vol.2805, 1996, pp.236-43.
- Windt, D et. al., to be published in Journal of Applied Physics , 2000.
- D.L.Windt, "IMD Software for modeling the optical properties of multilayer films", Computers in Physics, vol.12, no.4, 1998, pp.360-370. (<http://cletus.phys.columbia.edu/windt/index.html>)